

FURTHER EXPLORING THE POTENTIAL FOR ASSIMILATION OF UNMANNED AIRCRAFT OBSERVATIONS TO BENEFIT HURRICANE ANALYSES AND FORECASTS

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ABSTRACT

This study explores the potential of assimilating data from multiple instruments onboard high-altitude, long-endurance unmanned aircraft to improve hurricane analyses and forecasts. A recent study found a significant positive impact on analyses and forecasts of Hurricane Karl when an ensemble Kalman filter was used to assimilate data from the High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP), a new Doppler radar onboard the NASA Global Hawk (GH) unmanned airborne system. The GH can also carry other useful instruments, including dropsondes and the Hurricane Imaging Radiometer (HIRAD), which is a new radiometer that estimates large swaths of wind speeds and rainfall at the ocean surface. The primary finding is that simultaneously assimilating data from HIWRAP and the other GH-compatible instruments results in further analysis and forecast improvement for Karl. The greatest improvement comes when HIWRAP, HIRAD, and dropsonde data are simultaneously assimilated.

1. Introduction

New remote and in-situ observations of tropical cyclones provide unique opportunities to improve future hurricane forecasts. In the 2010 Genesis and Rapid Intensification Processes (GRIP) experiment, the National Aeronautics and Space Administration (NASA) for the first time used the Global Hawk (GH) unmanned aircraft system to gather observations from tropical cyclones. The GH is a unique observing platform because of its long flight duration (up to 26 h), high altitude (>18 km) and ability to carry large payloads (Braun et al. 2013).

Recently, Sippel et al. (2014) (hereafter S14) examined the potential for assimilation of GH observations to improve analyses and forecasts of Hurricane Karl, which was targeted by the GH during GRIP. Using an ensemble Kalman filter (EnKF), S14 assimilated data from the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP;

Li et al. 2011), one of a number of instruments compatible with the GH. They compared assimilation of Doppler velocity (V_r) and Doppler-derived VAD wind profiles (VWPs) and found a significant positive impact in analyses and forecasts of Karl for both data types, though forecast performance was better for VWP assimilation.

Building upon the success of S14, this study further explores the potential of assimilating data from multiple instruments onboard unmanned aircraft to initialize the hurricane vortex. The GH has carried a number of such instruments in addition to HIWRAP. Among those are dropsondes and the Hurricane Imaging Radiometer (HIRAD; Amarín et al. 2010), which is a new radiometer that estimates wind speeds and rainfall at the ocean surface. HIRAD measurements are similar to those of the Stepped Frequency Microwave Radiometer (SFMR; Uhlhorn et al. 2007) utilized by NOAA, but it uses cross-track scanning to provide a swath of wind speed information rather than just a line of wind data. A major motivation for the focus on those instruments here is that other studies (e.g., Aksoy et al. 2013, Zhang et al. 2011, Abernethy 2010, Majumdar et

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al. 2011) have shown similar kinds of observations to be useful for hurricane analysis and forecasting, but the utility of unmanned aircraft is only beginning to be explored.

2. Methodology and experimental setup

This study uses S14 as a springboard for further study of Hurricane Karl, which rapidly intensified in the Bay of Campeche in 2010. More details on the model configuration and data assimilation setup are found in S14, though some information can be found below along with descriptions of data sources and quality control measures. The experiment setup here is motivated by the findings of S14 and by the available instrument configurations on the GH. Because S14 found that assimilating VWP data produced superior forecasts compared to those using Vr, we use only HIWRAP VWP data here. Two of the experiments included here test assimilating HIWRAP VWP data in addition to either dropsonde or HIRAD data, and a third experiment includes all three instruments. Though operational agencies often employ targeting strategies for data assimilation purposes, such methods were not employed by either the Global Hawk or WB-57 during GRIP.

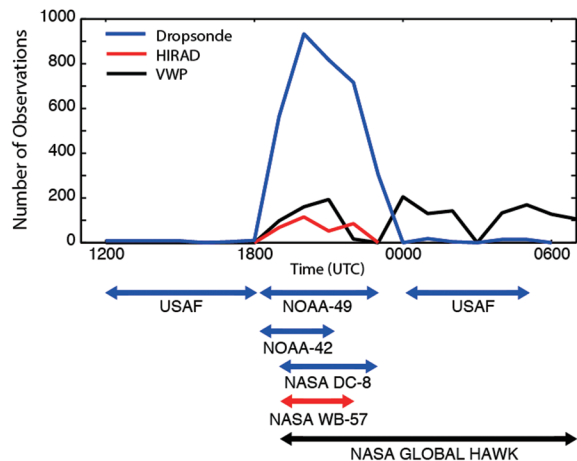
a. Data sources, quality control and data thinning

Though we wish to directly assess the benefit of simultaneously assimilating various GH-based data, a major limitation is that there is no single GH flight from which HIRAD, HIWRAP, and dropsondes have been deployed. During GRIP, HIWRAP was on the GH, and HIRAD flew on NASA's WB-57, which is a high-altitude manned aircraft. High-altitude dropsondes were unavailable during GRIP, so as a proxy we use those available from the NASA DC-8, the National Oceanographic and Atmospheric Association (NOAA) WP-3D, and the United States Air Force (USAF) WC-130. For reference, Fig. 1a shows the number of observations available from each instrument in addition to the aircraft on-station time, and Fig. 1b shows the spatial distribution of each observation type.

Extensive quality control and thinning measures were required for the HIWRAP (see S14) and HIRAD data. HIRAD surface wind speed and rain rate data were provided using a 4-frequency passive microwave retrieval algorithm by Amarin et al. (2012), and an example is shown in Fig. 2a. For assimilation purposes, these data were low-pass filtered and averaged over 3-km boxes to match the model grid spacing. The data were then further thinned, and only about 25% of the gridded data were retained for assimilation. Furthermore, all wind speeds below 15 m s⁻¹ were rejected due to large uncertainty in HIRAD wind retrievals at low speeds. Figure 2b shows HIRAD wind speeds after gridding, thinning, and rejection of low speeds.

All dropsonde data were quality controlled and thinned as well. NOAA and USAF data were obtained from TEMPDROP messages available online through the Atlantic Oceanographic and Meteorological Laboratory (AOML)

(a) Number of observations used from each instrument



(b) Horizontal distribution of observations

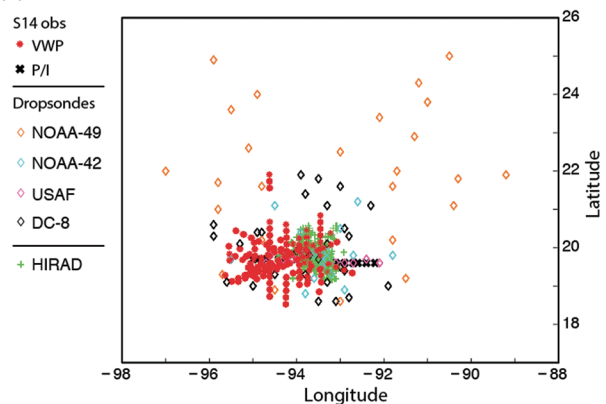


FIG. 1. The (a) temporal and (b) spatial distribution of observations used. In (a) the number of observations from the different instruments is shown as a function of analysis cycle. The on-station time for the various aircraft is shown beneath the graph with arrows that are color-coded to indicate which instrument each plane carried. In (b) the spatial distribution of observation is shown on a latitude-longitude grid. Markers for dropsondes indicate the release point.

Hurricane Research Division (HRD). TEMPDROPS are quality-controlled in real time and reported at significant and mandatory levels. Since TEMPDROPS do not report dropsonde location at individual levels, observation locations were calculated with code provided by HRD that uses the drop and splash locations as well as measured wind fields. Meanwhile, quality-controlled data from NASA dropsondes were subsampled down to both mandatory and intermediate levels.

Since no other datasets were assimilated in this study, it is unclear whether additional data would significantly change results here. Given Hurricane Karl was far from the densely observed United States mainland, any additional land-based observations would only give sporadic peripheral impact to the storm. Though satellite observations do provide better coverage near the storm, recent results from

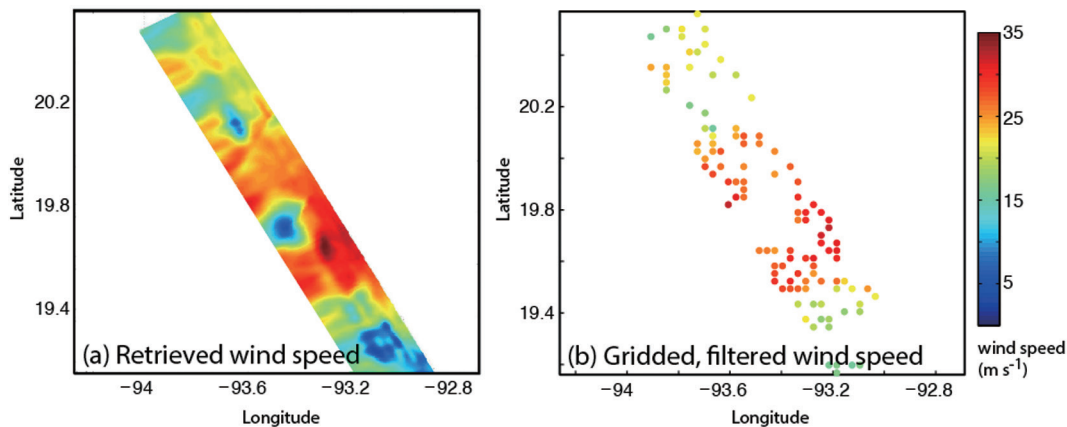


FIG. 2. HIWRAP-derived surface wind speeds from the 2000 UTC overpass of Karl (a) before and (b) after gridding and thinning.

Wu et al. (2015) suggest that satellite-derived observations such as atmospheric motion winds may be insufficient to accurately analyze the inner core even though they do provide a benefit to analyses and forecasts. More recent work by Zhang et al. (2016) has demonstrated promising performance through direct assimilation of satellite radiances from geostationary satellites (e.g., GOES-13). Future research is needed to generalize such findings, including evaluating direct assimilation of microwave satellite radiances.

b. Model and assimilation setup

The model setup is exactly the same as in Sippel et al. (2013, hereafter S13) and S14. We use the Weather Research and Forecasting model (WRF V3.1.1) with 35 vertical levels and two-way nesting to achieve 3-km grid spacing over the Bay of Campeche (see Fig. 1 of S13). A set of 30 initial and boundary condition perturbations to the Global Forecast System (GFS) analysis and forecast initialized at 00 UTC 16 September was used to create an ensemble of forecast realizations. For more information, please see S14.

The data assimilation experiments here follow the methodology outlined in S14. Those experiments assimilated hurricane position hourly from 1200 to 1800 UTC 16 September, and beginning at 1900 UTC position and minimum sea-level pressure (SLP) were assimilated along with VWP data. In addition, the experiments here assimilate HIRAD-derived wind speeds and dropsonde-observed horizontal wind components, specific humidity, and temperature with observation operators based on linear interpolation of model fields.

Covariance localization and assumed uncertainty likewise follow S14. Covariance for position and minimum SLP (hereafter P/I) was localized using a horizontal radius of influence (ROI) of 1200 km and a vertical ROI of 35

model levels. The assumed uncertainty for position is 20 km, and that for minimum SLP is 4 hPa. Meanwhile, VWP data were assimilated using the successive correlation localization (SCL) procedure first outlined in Zhang et al. (2009; hereafter Z09). Using SCL, a small percentage of VWP observations were assimilated with a horizontal ROI of 900 km, and successively more observations were assimilated with horizontal ROI of 300 and 100 km (more information on SCL and the application to the VWP data can be found in Z09 and S14). All VWP observations were also assimilated with a vertical ROI of 26 levels. S14 experimented with uncertainties of 2–4 m s^{-1} for this data, but for simplicity here we use only 3 m s^{-1} . Finally, the HIRAD data were assimilated using SCL with the same ROI as the VWP observations and an assumed uncertainty of 2 m s^{-1} , while sounding data were assimilated with the same ROI as P/I and with uncertainty prescribed as in the WRF data assimilation system (see Fig. 1 of Sippel and Zhang 2009).

3. Results

Figures 2–4 show the analyses from different assimilation experiments with the thin black lines denoting all VWP-assimilating analyses (i.e., with various assumed VWP observation uncertainty) and the gray line indicating a control experiment (CTRL) that only assimilates P/I only. S14 analyzed both the VWP-only and CTRL experiments. As in S14, results are compared with the observed maximum 10-m winds, minimum SLP, the radius of maximum winds (RMW), and radii of 64-kt winds (R64), 50-kt winds (R50), and 34-kt winds (R34). Instead of doing a quadrant-by-quadrant comparison for R64, R50, and R34, the average value is taken over all four quadrants as a proxy for the storm size.

a. Impact of adding additional data

In terms of the analysis intensity metrics, S14 found a

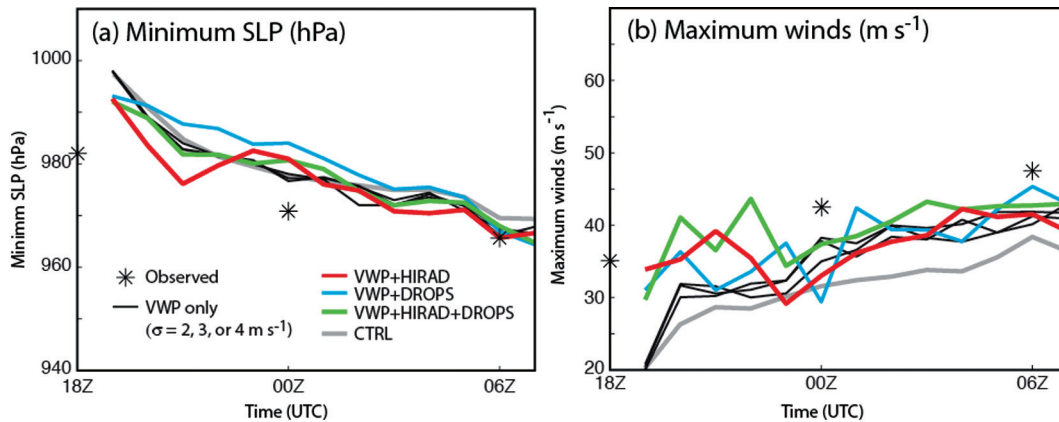


FIG. 3. EnKF-analyzed (a) minimum SLP and (b) maximum winds from the best-track data as compared with the S14 VWP-assimilating experiments and multi-instrument experiments.

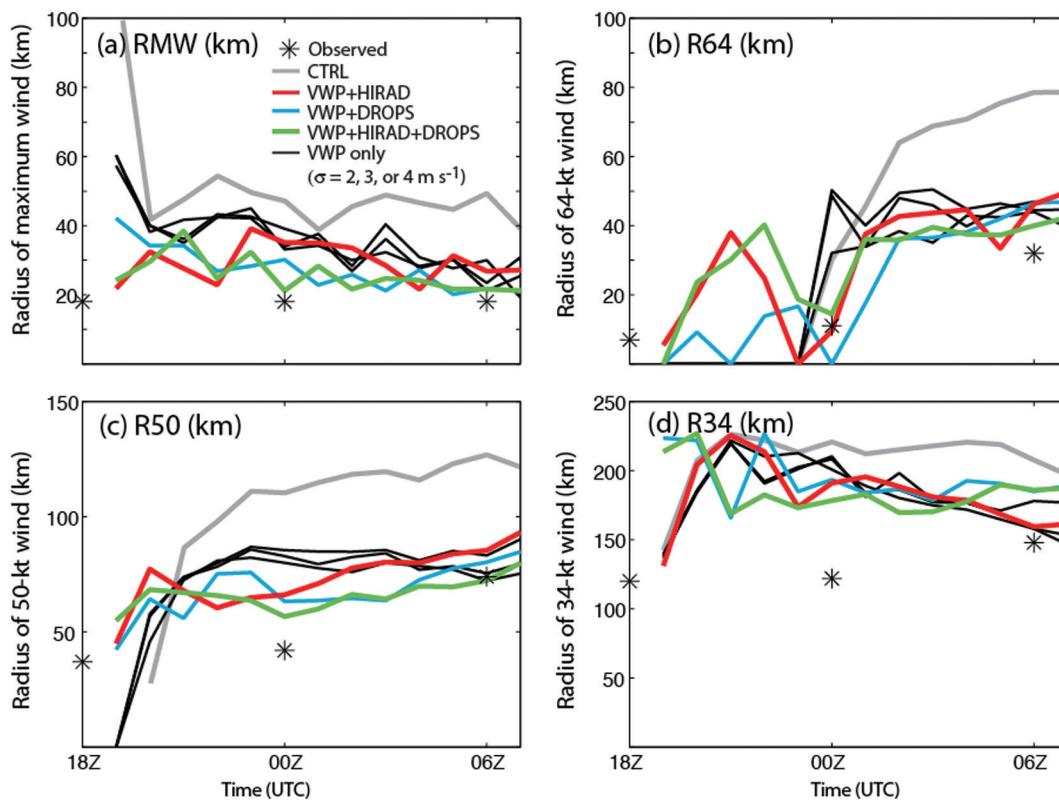


FIG. 4. As in Fig. 3 except for (a) RMW, (b) R64, (c) R50, and (d) R34.

substantial benefit from assimilating VWP data compared to only assimilating P/I. When only P/I are assimilated, the analyzed vortex is far too large and typically weak (Figs. 3–4). Also, the vertical extent of the circulation tends to be somewhat limited (not shown). When VWP data is added, much of this error is corrected.

The benefit of assimilating additional data beyond VWP

is not uniform, but the results do suggest a maximum benefit from assimilating data from all three sources. For example, when dropsondes are added to P/I and VWP data, the maximum winds spin up faster (Fig. 3b) but are otherwise similar to those in the three VWP-only experiments. However, the analysis minimum SLP is actually somewhat less accurate (Fig. 3a). Meanwhile, when HIRAD wind

speed data are added to the VWP observations, there is a quicker intensity spinup, but this benefit is short-lived, and the analysis intensity becomes commensurate with that of the VWP-only experiments as soon as HIRAD is no longer available. The deficiencies of the two-instrument experiments vanish when all three data types are assimilated. In this instance, the minimum SLP analysis is generally commensurate with the VWP-only experiments, but the maximum winds are generally higher and thus more accurate. Though the maximum winds do also decrease when HIRAD data ends, they remain marginally higher than in the other experiments.

The benefit of assimilating from multiple sources is clearer for the wind radii metrics in Fig. 4. For both the RMW (Fig. 4a) and R50 (Fig. 4c), the addition of one or two data sources results in a more accurate storm size. Though the benefit of assimilating HIRAD data again diminishes soon after the instrument leaves, when either dropsondes or both HIRAD wind speeds and dropsondes are assimilated in addition to VWP observations, both R50 and the RMW are superior for nearly the entire assimilation period. Meanwhile, for R34 (Fig. 4d), only the experiment with all three sources is distinguishably better than the VWP-only experiments. Finally, there appears to be no net benefit of additional data for R65 (Fig. 4b).

b. Comparison of EnKF-initialized forecasts

Here we compare short-term deterministic forecasts initialized from the EnKF analyses with the best track data and deterministic forecast without assimilation (NODA). In S14 forecasts were initialized at 0000, 0200, 0400, and 0600 UTC 17 September, however here we examine those initialized at 2200 UTC 16 September and 0200 and 0600 UTC 17 September. The forecasts from the 16th are necessary to obtain a sample when all three instruments were on station, while those shown from the 17th are representative of the 0000 and 0400 UTC forecasts (not shown).

S14 found that assimilating VWP data in addition to P/I improved forecasts considerably, which is consistent with the aforementioned improved analyses. Some of the results from that study, shown in Fig. 5, reveal that the CTRL analyses undergo strong adjustment so that the change in minimum pressure and maximum winds are inconsistent with one another. The result is that CTRL-initiated forecasts never attain a central pressure anywhere close to that observed, and the maximum winds also tend to be too weak. Much of this error is mitigated by assimilating VWP data as well.

The results of the multi-instrument experiments show that there is some benefit from additional sources of data, though the benefits are again not uniform. For example, Fig. 5 shows that assimilating HIRAD data in addition to VWP data generally does not impact forecast accuracy. However, assimilating dropsondes and VWP data results in an obvious improvement in forecast track, and run-to-run

track consistency is greater when dropsondes are assimilated. The best results come from assimilating data from all three sources. In particular, forecasts initialized from analyses that assimilate VWP, HIRAD, and dropsonde data are most accurate in their depiction of the minimum SLP achieved, and they have the most run-to-run intensity consistency. Though the maximum winds in these forecasts are somewhat high at the time of peak intensity, they are still within the envelope of uncertainty for the observed winds (i.e., about 5 m s⁻¹). Meanwhile, the track accuracy when all sources are assimilated is roughly the same as in the experiments that only assimilate VWP and dropsonde data.

4. Concluding remarks

This study is intended as a follow-up to S14 that further explores the potential of assimilating data from high-altitude, long-endurance unmanned aircraft to initialize the hurricane vortex. S14 found a significant positive impact on analyses and forecasts of Hurricane Karl (2010) when they used an EnKF to assimilate data from the HIWRAP radar on NASA's Global Hawk (GH). The GH has carried other useful instruments, including dropsondes and HIRAD, which is a new radiometer that estimates large swaths of wind speeds and rainfall at the ocean surface. Though we wish to directly assess benefit of simultaneously assimilating these various GH-based data, a major limitation is that there is no single GH flight from which HIRAD, HIWRAP, and dropsondes have been deployed. During Hurricane Karl, HIWRAP and HIRAD flew on separate aircraft, and high-altitude dropsondes were unavailable. As a proxy for GH dropsondes, we use those available from other aircraft.

The results here suggest that assimilating data from the additional sources is beneficial for analyses, and the strongest benefit comes when all three sources are assimilated simultaneously. Adding HIRAD-derived wind speeds to the VWP wind estimates has an immediate analysis benefit in terms of both maximum intensity and storm size, though that benefit disappears when HIRAD data are no longer available. It could be that a longer HIRAD on-station time would result in longer-term analysis benefits, though that possibility is currently impossible to assess. Meanwhile, adding dropsondes to the VWP data helps to spin the analysis up faster, though the only lasting positive impact is on storm size. Finally, assimilating data from all three sources has a consistent positive impact on both maximum intensity and storm size.

The greatest impact on forecasts also comes from assimilating data from all three sources. For example, assimilating HIRAD data in addition to VWP data generally does not impact forecast accuracy. Though assimilating dropsondes and VWP data results in an obvious improvement in forecast track and run-to-run track consistency, the minimum SLP forecast is still somewhat inaccurate. However, when HIRAD is assimilated with the other two data-

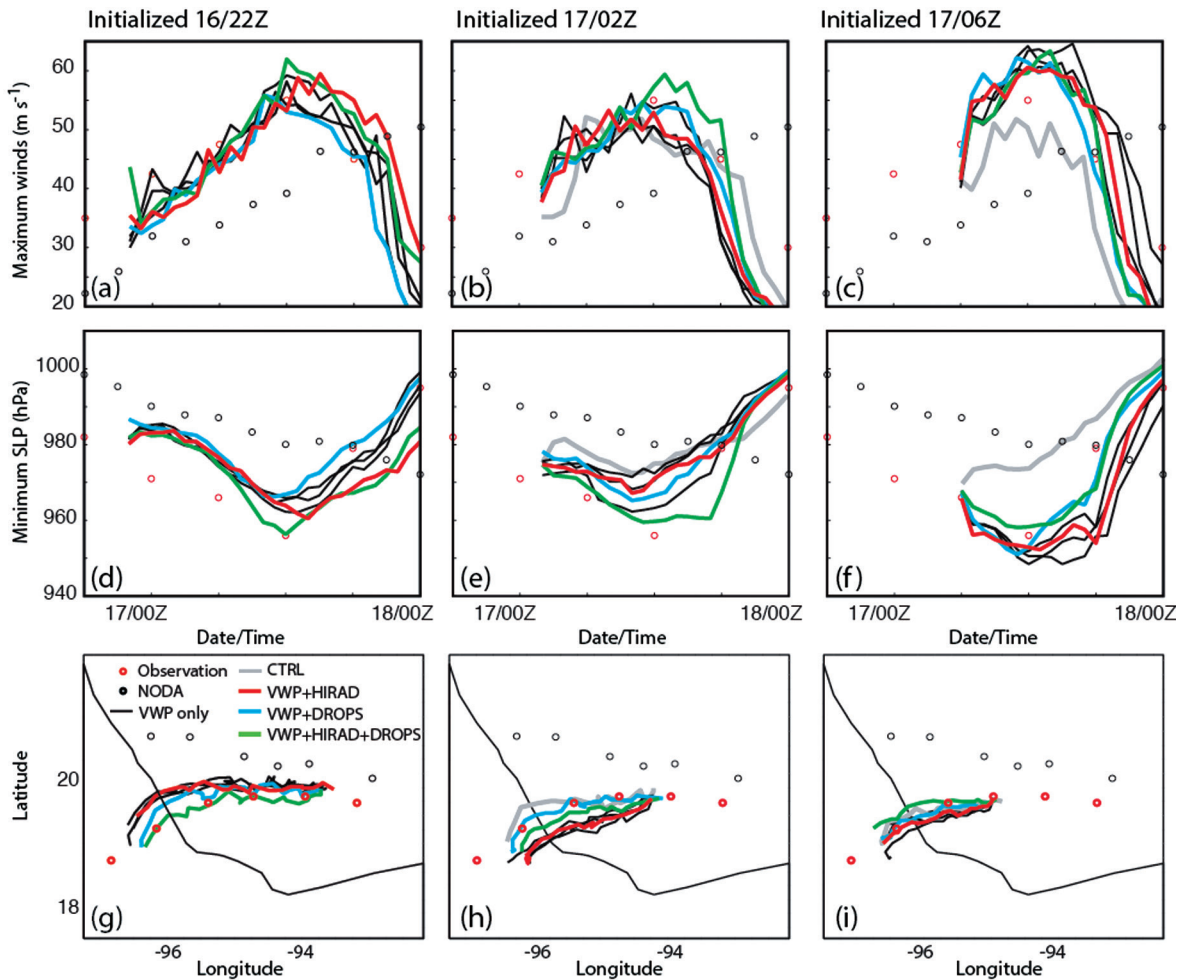


FIG. 5. The evolution of best-track (a-c) maximum winds, (d-f) minimum SLP, and (g-i) position compared to that from NODA and deterministic forecasts initialized from the EnKF analyses at (left) 2200 UTC 16 September, (middle) 0200 UTC 17 September, and (right) 0600 UTC 17 September.

sets, both the track and minimum SLP forecasts accuracy increases.

There are several reasons for the improvement when multiple datasets are assimilated. First, the VAD data is limited to radials in precipitating regions of the storm so that there are large gaps between radial legs and no observations in no-precipitating regions. Furthermore, the VAD observations are only assimilated between altitudes of 2 and 8 km (S14), so analyses near the surface and in upper levels must rely completely upon sampling covariance. The addition of dropsondes and HIRAD data serves to fill in the horizontal and vertical gaps and to add observations from outside the precipitation (e.g., Fig. 1). Another important consideration is that the VAD only estimates the winds so that corrections to thermodynamic variables must rely completely upon cross covariance. With the addition of dropsondes, thermodynamic variables are directly observed, which likely provides superior updates for the

analyses.

Though for the sake of brevity no diagnosis of fit to available observations has been completed here, the ability of the analyses to capture the three-dimensional dynamic thermodynamic fields can be inferred from the behavior of both the analyses and forecasts. First, the fact that the analyses show increasing fit to multiple wind radii, maximum winds, and the pressure field is a good indication that the overall mass and wind fields are likely to be accurate. Second, the forecasts initialized from the analyses show little to no spindown that is typical of imbalance between the mass and wind fields. These two factors combined strongly indicate that assimilation here accurately captures the full three-dimensional fields of Hurricane Karl.

In summary, the results here strengthen the S14 conclusion that unmanned, long-endurance aircraft like the GH can be used to improve hurricane analysis and forecasting. By combining data from multiple instruments, each of

which can be installed upon NASA's GH, further improvements were made to those of S14. While these results are subject to the limitations of examining one case, the GH will continue to be used in the future for hurricane observations, which will provide the opportunity for further evaluation of the potential of this unique resource.

Acknowledgements

TEMPDROP data sets and interpolation code were provided by HRD, and we specifically thank Sim Aberson and Kathryn Selwood from HRD for assistance with NOAA and USAF dropsondes. We also thank W. Linwood Jones, Saleem Sahawneh and Yazan Hejazin from the University of Central Florida for assistance with HIRAD data. The first author completed most of this work under the employment of Morgan State University through the GESTAR agreement with NASA. Funding for this work came the Hurricane and Severe Storm Sentinel Investigation under NASA's Earth Venture Program and from the NASA New Investigator Program. The simulations were conducted on NASA Center for Climate Simulation facilities.

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